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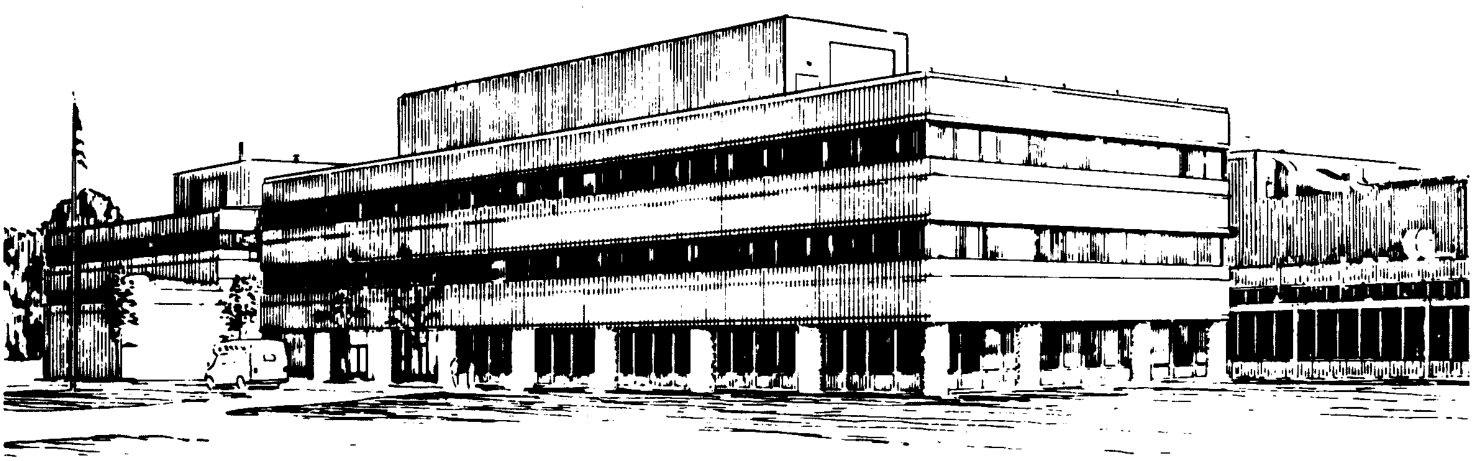

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Effect of Plasma Rotation on Sawtooth Stabilization by Beam Ions

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The sawtooth period in JET ELM-free H-Mode plasmas is increasing with Neutral Beam Injection (NBI) power. For injected power $P_{NBI} > 12MW$ no large sawtooth crash is observed during the ELM-free period. However, as the edge stability is improved and external kink modes and ELMs are delayed, a possible sawtooth crash at a high plasma beta becomes a concern. In JET DT experiments, delaying sawteeth was found to be crucial in the quest for high fusion power [1]. Fast particles are known to provide stabilizing effect on sawteeth (see for example[2]), however, sawtooth stabilization by NBI ions is not clearly understood, since NBI ions are usually not "fast" enough to stabilize the $m/n = 1/1$ internal kink mode which is believed to cause the crash. In order to understand the observed sawteeth stabilization in tokamak experiments with NBI heating, the internal kink $m/n = 1/1$ mode stability of JET plasmas was modeled using the NOVA-K code[3], which is also benchmarked with the nonperturbative version of NOVA[4] and the M3D code[5]. Comparison of $m/n = 1/1$ mode stabilization by NBI ions in JET and TFTR and application of the nonlinear ω_*-stabilization criteria[6] is given.

1 Code description and benchmarking

To study the effects of the 1/1 internal kink mode stabilization by NBI ions we will use the recently improved perturbative code NOVA-K, which computes quadratic form terms including hot particles

$$\delta K = \delta W \equiv \delta W_{MHD} + \delta W_{kh},\ \delta K = \omega^2 \int \rho \xi^2 d^3 r. \tag{1}$$

and the 1/1 mode structure without fast particles. Unlike the ideal MHD case, where $\delta K \sim \omega^2$, we will make use of the assumption that $\delta K \sim \omega$, which produces the following dispersion relation[4] to account for the fast particle kinetic potential energy

$$-i\omega \left(1 + \frac{\omega_T^2}{\omega_s^2 - \omega^2}\right) = \gamma_{MHD} \left(1 + \frac{\gamma_h}{\gamma_{MHD}}\right),\ \frac{\gamma_h}{\gamma_{MHD}} = \frac{\Re \delta W_{kh}}{\delta K}, \tag{2}$$

where $\omega_T^2 = 2\gamma_s P_c \kappa/\rho$, $\omega_s^2 = (1/2)\gamma_s \beta_c \omega_A$, κ - curvature, $\gamma_s = 5/3$, ρ is plasma mass. One can see that the real part of the fast particle contribution to the potential energy $\Re\delta W_{kh}$ can give stabilization and is computed in NOVA-K according to the following formula [3], which includes particle finite orbit width (FOW) and finite Larmor radius (FLR) effects

$$\delta W_{kh} = -(2\pi)^2 e_\alpha c \int dP_\varphi d\mu d\mathcal{E} \tau_b \sum_{m,m',l} \frac{X^*_{m,l}(\omega - \omega_*) X_{m',l}}{\omega - \overline{\omega_d}} \frac{\partial F_h}{\partial \mathcal{E}}, \tag{3}$$

where the integration is performed over the particle phase space $P_\varphi, \mu\, \mathcal{E}$ in general tokamak geometry, τ_b is the particle bounce time, $X_{m,l}$ gives wave - particle interaction power exchange, F_h is the fast particle equilibrium distribution function, $\omega_* = -i \frac{\partial F/\partial P_\varphi}{\partial F/\partial \mathcal{E}} \frac{\partial}{\partial \varphi}$, and ω_d is particle toroidal drift frequency. One can see from Eq.(3) that one needs $\omega < \omega_d$ for the stabilization to occur. In other words, since the 1/1 mode frequency is associated with plasma diamagnetic frequency ω_* and $\omega_d \sim \mathcal{E}$, particles should be energetic enough

$\omega_* < \omega_d$ to provide the stabilization. The expression Eq.(3) can be modified to include the effect of plasma rotation on fast particle contribution by simply substituting the mode frequency $\omega \rightarrow \omega - \Omega_E(\psi)$, where $\Omega_E(\psi)$ is plasma toroidal rotation as a function of poloidal flux. This can be shown more rigorously [7]. The effect of the rotation coming from the denominator is dominant.

We have performed the benchmark of NOVA-K with its previous nonperturbative version NOVA-2 and with M3D codes for one particular case with circular plasma cross section and the following plasma parameters: major radius $R_0 = 2.62m$, minor radius $a = 0.95m$, plasma central beta $\beta_{pl}(0) = 5\%$, fixed total beta on Fig.1 ($\beta_{pl} + \beta_h = const$), and toroidal magnetic field $B = 4.45T$. Deuterium hot slowing down ions with cutoff velocity $v_h = 10^9 cm/sec$, ratio to central Alfvén velocity $v_h/v_{A0} = 1$, major radius to particle Larmor radius ratio $R/\rho_h = 55.6$. The NOVA-2 code is a non-perturbative code, which calculates the mode structure with fast particles included in the quadratic form. M3D is a non-linear code, with fast particles included. One can see that the eigenfrequency and the growth rates of fishbone branch are reproduced by NOVA-2 and M3D. Linear stabilization phase of $m/n = 1/1$ kink mode agrees for three codes. Fishbone frequency is of order of particle toroidal precession drift frequency $\omega_{dr\varphi}/\omega_{A0} = 0.49$, where $\omega_{A0} = v_{A0}/R$.

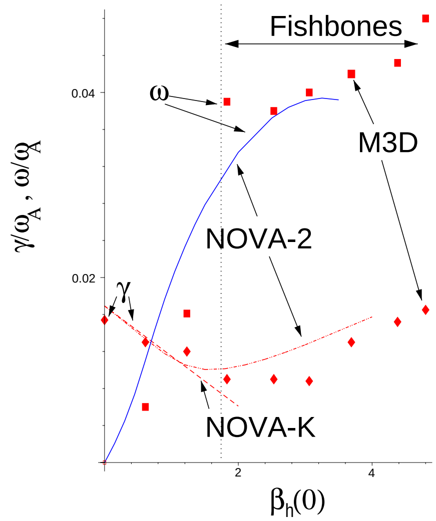

Figure 1: *Codes benchmark*

2 Properties of Fast Particle Stabilization of $m/n = 1/1$ mode in JET.

JET high performance shot #42976 at $t = 13.3sec$ was chosen to study the properties of hot particle stabilization of 1/1 mode. TRANSP was used to provide plasma parameters, which in this case were $B = 3.7T$, $R_0 = 2.92m$, $a = 0.94m$, $P_{NBId} = 11.9MW$, $P_{NBIt} = 10.5MW$, $P_{ICRH} = 3.1MW$. Summary of the basic calculations for stability study by NOVA-K with sheared plasma rotation velocity is given in the following table with growth rates contributing to the dispersion Eq.(2):

	MHD	ICRH, $\lambda_0 \equiv R/R_0$	NBI-D	NBI-T	α-particle
Distribution		Maxw., Res. layer at $\lambda_0 = 0.96$	Slow.Down	Slow.Down	Slow.Down.
Energy,keV		$(T_H =)200$	76	150	3520
$\beta_0, \%$	5.81	0.65	0.25	0.44	0.6
$\gamma/\omega_A, \%$	1.5	-0.9	-0.07	-0.17	-0.53

In the NOVA-K analysis the 1/1 mode is assumed to rotate with a frequency equal to the plasma rotation frequency at the $q = 1$ surface while it has a global structure and can interact with fast particles at different minor radii.

We have found that the FLR effects are negligible for fast particle stabilization, while FOW effects are small. FOW is reducing $\alpha-$particle and ICRH contributions by $\sim 20\%$, while only slightly modifying the NBI term in Eq.(2). The distribution function of NBI ions needs special calculation and for the sake of simplicity is assumed to be slowing down in velocity and Gaussian in pitch angle $F_{b\lambda} = exp(-(\lambda - \lambda_0)^2/\Delta\lambda^2)$, where $\lambda = \mu B/\mathcal{E}$. The geometry of the injection suggests that NBI ions are mostly passing particles. However, such effects as beam finite cross section, finite toroidicity, FOW, FLR, and Coulomb collisions can produce broad pitch angle distributions[8]. We used $\lambda_0 = 0.3$ and $\Delta\lambda = 0.7$ calculating results above. The results are not sensitive to $\lambda_0 = 0.3$ if $\lambda_0 \ll 1$, but are sensitive to $\Delta\lambda$, illustrated in Fig.2. Note that $\Delta\lambda = 0$ corresponds to single pitch angle passing particle distribution and $\Delta\lambda = \infty$ to isotropic distribution.

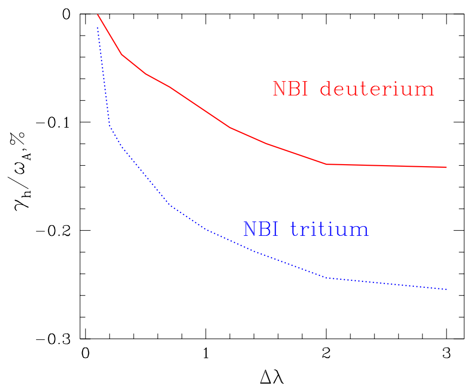

Figure 2: *NBI stabilization dependence on the width of the pitch angle distribution .*

The contribution of ICRH ions is shown in Fig.3 to be very sensitive to the position of the resonance layer, which determines pitch angle λ_0, and the temperature of the Maxwellian energy distribution. As the resonance layer shifts inwards the stabilization decreases. ICRH ions can even contribute to destabilization of 1/1 mode if resonance layer is $< 2.9m$. Note that ICRH ions present the largest contribution to the stabilization of 1/1 mode. This is due to the fact that ICRH ions are all trapped, while their beta is comparable with $\alpha-$particle beta.

The effect of the plasma rotation is modelled by prescribing the toroidal co-current rotation velocity in the form $\Omega_\varphi = 2.15(1-\psi)^{0.75} + 0.05$, $10^5 rad^{-1}$, which is computed by TRANSP. We study this effect on different plasma species introducing the rotation enhancement factor as shown in Fig.4(left). The stabilization of 1/1 mode is sensitive to the toroidal sheared rotation if its toroidal precession is comparable with the variation of the rotation within the $q = 1$ surface $\omega_{d\varphi} \sim r\partial\Omega_\varphi/\partial r$. Hence, the rotation is less important for ICRH ions and $\alpha-$particles then for beam ions, which have much smaller precession frequency. The co-rotating plasma with the velocity shear supports the stabilization effectively because it increases particle energy by providing extra toroidal precession.

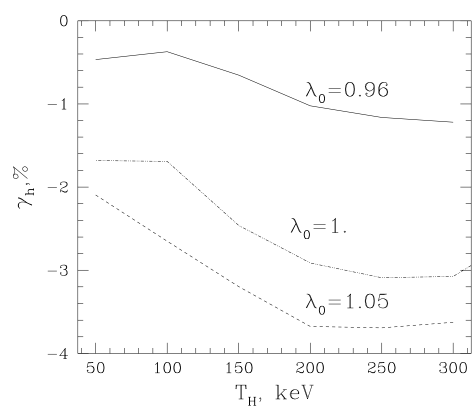

Figure 3: *ICRH ion stabilization dependence on their temperature for different resonance layer positions.*

3 JET NBI α-particle experiments

Five similar JET discharges with different tritium concentrations were analyzed using the NOVA-K code. As the tritium concentration increases, both the calculated 1/1 mode damping rate and the period between the sawteeth τ_{saw} increase. The analysis indicates that such "mass" effect come from increasing beam ion beta:

$$\gamma_h \sim \beta_{hNBI} \sim S_{NBI}\tau_{se},$$

where the slowing down time is proportional to the beam ion mass $\tau_{se} \sim m_{NBI}$. The results are presented on Fig. 4(right). Analysis of the co-rotating plasma shows reduction of the stabilization from fast particle for given discharges. Slightly better correlation between the measured sawtooth period and the NBI damping rate is observed in rotating plasma.

4 Linear vs. Nonlinear ω_*-stabilization.

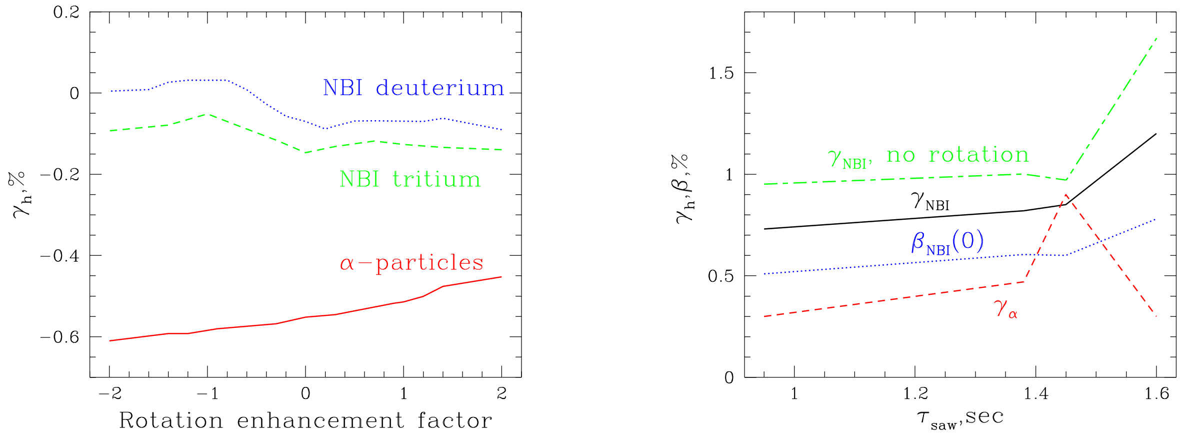

Figure 4: *Effect of plasma rotation on the NBI and $\alpha-$particle stabilizing contributions (left) and analysis of the NBI heated $\alpha-$experiments on JET.*

TFTR demonstrated nonlinear ω_*-stabilization in supershots[9]. It was shown that the stability criteria works well in the conditions when ω_* is larger than the ideal MHD 1/1 mode growth rate:

$$r_1 q'_{1crit} \equiv 1.4 \left(\frac{m_i}{2m_p Z_{eff}}\right)^{1/6} \beta_1^{2/3} \left(\frac{|n'_e|\,R}{n_e}\right)^{2/3} \left(\frac{|p'|\,R}{p}\right)^{1/3} > r_1 q'_1. \quad (4)$$

Analysis of three TFTR shots shown in Tab.1 shows smaller effect from NBI than in JET discharges: in JET plasma for the analyzed NBI only shots $r_1 q'_{1crit} < r_1 q'_1 \Rightarrow$ small

	sawtooth	γ_b/ω_A, %	β_{b0}, %	$r_1 q'_{1crit}$	$r_1 q'_1$
#65611	no	0.29	2.2	0.72	0.29
#65612	yes	0.2	1.05	0.359	0.396
#68262	NBI suppressed	0.3	1.2	0.56	0.29

Table 1: *TFTR* 1/1 *stabilization modeling results, where* $\gamma_{MHD}/\omega_A \simeq 3-8\%$.

ω_*-stabilization effect. On the other hand NBI ions, supported by sheared rotation can provide stabilization of 1/1 internal kink mode in JET.

5 Summary

Stabilizing effects on 1/1 internal kink mode by NBI hot ions is demonstrated for JET NBI alpha experiments in high performance discharges. Plasma sheared rotation, which is strong in JET, reduces the stabilizing effect of NBI ions on the growth rate of 1/1 internal mode. Alpha particles offer a strong contribution to the sawtooth stabilization in high fusion plasma. Mass dependence of fast beam ion contribution to δW is shown to be consistent with the increased sawtooth period for experiments with larger concentration of tritium NBI. While ω_*-stabilization model by L.Zakharov appears to be consistent with TFTR sawtooth suppression in supershots, it cannot explain the increased sawtooth period with increased NBI ion beta, because of low ω_*in JET experiments.

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